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Nucleon-number scalings of anisotropic flows and nuclear modification factor for light nuclei in the squeeze-out region

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Abstract. The number of nucleon (NN) scaling of the directed flow v_1 and elliptic flow (v_2) as well as the nuclear modification factor (R_{cp}) are tested for light nuclei which are produced in $0.4A$ GeV $^{197}Au+^{197}Au$ collisions at different impact parameters with two different in-medium nucleon-nucleon cross sections in a framework of an isospin-dependent quantum molecular dynamics (IQMD) model. In that energy domain, the emission of light nuclei can be well described by the squeeze-out phenonomenon. The results show a nice NN scaling behavior for flow parameters v_1, v_2 and R_{cp}. These results demonstrate that the nucleon coalescence mechanism is responsible for nucleon-number scaling of above physical observables in squeeze-out region in heavy-ion collisions at intermediate energy.

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1 Introduction

In intermediate-energy heavy-ion collisions (HIC), the collective flow is one of the important observables which can reflect the early stage of heavy ion reaction, evolution dynamics, in-medium nucleon-nucleon cross section [1–7], as well as the information on the nuclear equation of state (EOS) [8–16]. Many studies of anisotropic flows, namely the directed flow (v_1) and the elliptic flow (v_2) revealed the properties and origin of the collective motion through exploring the dependences for anisotropic flows on beam energy, fragment mass, impact parameter and so on in HIC [8–16].

The number-of-nucleon (NN) scaling of anisotropic flows was first proposed by Yan and Ma *et al.* in low-intermediate energy heavy ion collisions through a framework of a quantum molecular dynamics model [17,18]. This scaling states that when the anisotropic flows were scaled by the nucleon-number of light nuclei, these scaled flows will follow the same curve as a function of rapidity or transverse momentum per nucleon regardless of the mass of light nuclei [18]. This phenomenon can be naturally interpreted by a nucleonic coalescence mechanism for the formation of light nuclei at kinetic freeze-out stage in the reaction system. However, the earlier focus of the coalescence mechanism is only on the spectra of kinetic energy or momentum of light nuclei in heavy ion collisions [19] but not on flow behavior.

After the first prediction on number of nucleon scaling of flows in heavy-ion collisions at lower energies [17,18], the same concept of number-of-nucleon scaling of elliptic flow was followed by a dynamical model as well as a multiphase transport (AMPT) model calculations at ultra-relativistic energy [20–22]. Later on the number-of-nucleon scaling of anisotropic flows for light nuclei have been experimentally confirmed in Au + Au collisions at much higher energies, such as 200, 62.4, 39, 27, 19.6, 11.5, and 7.7 GeV at the BNL Relativistic Heavy Ion Collider (RHIC) [23], which illustrates that the light nuclei at RHIC energies are also formed by nucleonic coalescence mechanism at the freeze-out stage but not directly by the quark coalescence mechanism. At both lower and relativistic energies, the elliptic flow demonstrates the positive values: the former stems from the collective rotational motion due to the dominated mean field, and the later origins from the strong pressure of the overlapping participant region. In both cases, the NN scaling has been examined. However, in middle energy region where the negative elliptic flow might emerge due to the squeeze-out behavior of particle emission, NN scaling of flows is not yet checked so far.

On the other hand, the number-of-constituent-quark scaling of nuclear modification factor (NMF) for pions and protons as well as the number-of-nucleon scaling of NMF for light nuclei have been first proposed by one of the authors [24], and they were experimentally supported for Au + Au and Pb + Pb collisions at NA49, RHIC and LHC energies. However, the similar NN scaling behavior of

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NMF is not yet examined in intermediate energy heavy ion collisions. In this energy domain, the isospin-dependent quantum molecular dynamics (IQMD) model [25–27] is very successful for studying reaction dynamics, such as for spectra analysis, flow analysis as well as the nuclear modification factor analysis [28]. Therefore it will be of very interesting to test if the R_{cp} of light nuclei can be scaled by the number of nucleon scaling.

Based upon the above arguments, in this article, we use an isospin-dependent molecular dynamics (IQMD) model to simulate 0.4A GeV Au + Au collisions at different impact parameters with two sets of in-medium nucleon-nucleon cross section. The anisotropic flows and R_{cp} of different light nuclei especially in terms of the coalescence mechanism are systematically investigated, and the squeeze-out behavior was cleanly observed by the negative elliptic flow. In this work the R_{cp} is obtained by dividing the spectra in the centrality of 0-10%, 10-20%, and 20-40% to the one in the centrality of 60-80%. Dependences of the mass number of the anisotropic flows and the nuclear modification factor are surveyed, and the nucleon-number scaling of light nuclei on the anisotropic flows and R_{cp} are also found.

2 Theoretical descriptions

2.1 Definition of the directed and elliptic flows

Anisotropic flow is defined as the different n-th harmonic coefficient v_n of an Fourier expansion of the particle invariant azimuthal distribution

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n\phi), \tag{1}$$

where the reaction plane was defined by a plane of the z-axis along the beam axis and x-axis along the impact parameter axis in the coordinate system and ϕ is the azimuthal angle between the transverse momentum of the particle and the reaction plane. For a given rapidity the anisotropic flows are evaluated according to

$$v_n\left(p_t\right) = \langle \cos(n\phi) \rangle, \tag{2}$$

where $\langle \cos(n\phi) \rangle$ denotes the average over the azimuthal distribution of particles with transverse momentum p_t. Specifically, the directed flow

$$v_1 = \langle \cos\phi \rangle = \left\langle \frac{p_x}{p_t} \right\rangle, \tag{3}$$

and elliptic flow

$$v_2 = \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle, \tag{4}$$

where p_x and p_y are components of momentum, and $p_t = \sqrt{p_x^2 + p_y^2}$ is transverse momentum.

2.2 Definition of nucleon-number scaling of nuclear modification factor

The nuclear modification factor R_{cp} is a probe to study the nuclear medium effect in nucleus-nucleus collisions, it is defined as a ratio of the particle yield in central collisions to that in peripheral collisions [29, 24, 28], i.e.

$$R_{cp} = \frac{\left[d^2N/2\pi p_T dp_T dy/\left\langle N_{bin}\right\rangle\right]^{central}}{\left[d^2N/2\pi p_T dp_T dy/\left\langle N_{bin}\right\rangle\right]^{peripheral}}, \tag{5}$$

where $d^2N/2\pi p_T dp_T dy$ is the particle invariant differential yield of the transverse momentum spectra p_T, $\langle N_{bin}\rangle$ means the average nucleon-nucleon binary collision number per event. Now, we focus on the coalescence mechanism for the formation of light nuclei similar to that for the production [30] or elliptic flow [3, 31] of hadrons in relativistic heavy-ion collisions. The formation of light nuclei can be described by the coalescence mechanism as follows:

$$\begin{aligned} E_A \tfrac{d^3N_A}{d^3P_A} &= B_A \left(E_p \tfrac{d^3N_p}{d^3P_p}\right)^Z \left(E_n \tfrac{d^3N_n}{d^3P_n}\right)^{A-Z} \\ &= B_A \left(E_p \tfrac{d^3N_p}{d^3P_p}\right)^A, \end{aligned} \tag{6}$$

where $P_p = P_n = P_A/A$ and A is the number of protons in light nuclei. The coefficient B_A is the probability for coalescence of nuclei with mass number A, which depends on momentum as well as the fireball volume in coordinate space [32]. The coefficient B_A can be extracted from data or calculated by the coalescence mechanism [32]. The number of nucleon scaling for the R_{cp} of light nuclei can be deduced from Eq. 5 and Eq. 6 [24] :

$$R_{cp}^{*} = \left(\frac{B_{A,c}}{B_{A,p}}\right)^{-1/A} \left(R_{cp}\left(A \cdot p_T\right)\right)^{1/A} \left(\frac{\langle N_{bin}\rangle^c}{\langle N_{bin}\rangle^p}\right)^{1/A-1}. \tag{7}$$

Here, the index c and p stands for the central collisions and peripheral collisions, respectively. R_{cp}^{*} is the scaled nuclear modification factor to scale proton R_{cp} together. Then we can try to scale R_{cp} of light nuclei by the following formula [24]:

$$\widetilde{R}_{cp}^{*}\left(p_T\right) = \left(R_{cp}\left(A \cdot p_T\right)\right)^{1/A} \left(\frac{\langle N_{bin}\rangle^c}{\langle N_{bin}\rangle^p}\right)^{1/A-1}, \tag{8}$$

and

$$\widetilde{R}_{cp}^{*}\left(p_T\right) = R_{cp}^{*}\left(p_T\right) / \left(\frac{B_{A,c}}{B_{A,p}}\right)^{-1/A}. \tag{9}$$

2.3 The isospin-dependent quantum molecular dynamics model

In the following discussion, we introduce the isospin-dependent quantum molecular dynamics (IQMD) model briefly. The quantum molecular dynamics model is a n-body transport theory, it describes heavy-ion reactions from intermediate to relativistic energies. The main parts of QMD transport model include the following: the initialization of the

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projectile and the target, nucleon propagation in the effective potential, the collisions between the nucleons in a nuclear medium, the Pauli blocking effect, and the numerical test. The isospin-dependent quantum molecular dynamics model is based on the QMD transport model with the isospin factors taken into account [25,33]. As we know, the main components of the dynamics in heavy-ion collisions (HICs) at intermediate energies include the mean field, two-body collisions, and Pauli blocking. Therefore, it is important for these three components to include isospin degrees of freedom in the IQMD transport model.

In particular, the density-dependent Skyrme potential U_{Sky} reads when the momentum dependent potential is included

$$U_{Sky} = \alpha(\frac{\rho}{\rho_0}) + \beta(\frac{\rho}{\rho_0})^{\gamma} + t_4 ln^2[\varepsilon(\frac{\rho}{\rho_0})^{2/3} + 1]\frac{\rho}{\rho_0}, \quad (10)$$

where ρ and ρ_0 are total nucleon density and its normal value, respectively. The parameters α, β, γ, t_4 and ε are related to the nuclear equation of state [34,35] and listed in Table I, where $K = 200$ or 380 MeV means the soft- or the stiff- momentum dependent potential, respectively.

Table 1. The parameters of the interaction potentials.

α	β	γ	t_4	ε	K
(MeV)	(MeV)		(MeV)	(MeV)	(MeV)
-390.1	320.3	1.14	1.57	21.54	200
-129.2	59.4	2.09	1.57	21.54	380

In this model, the particles are identified using a modified isospin-independent coalescence description, i.e., two nucleons are assumed to share the same cluster if their centers are closer than a distance of 3.5 fm and their relative momentum smaller than 0.3 GeV/c. If the nucleon is not bounded by any clusters, it is treated by an emitted (free) nucleon. In the IQMD model, the in-medium nucleon-nucleon cross section (NNCS) is represented by the formula:

$$\sigma_{NN}^{med} = \left(1 - \eta\frac{\rho}{\rho_0}\right)\sigma_{NN}^{free}, \quad (11)$$

where η is the in-medium NNCS reduction factor and σ_{NN}^{free} is the available experimental NNCS from Particle Data Group. The above in-medium NNCS reduction factor η varied from 0 to 1 and the relationship between η and the in-medium effect is opposite in this expression. In particular, the factor $\eta \approx 0.2$ has been found better to reproduce the flow data.

3 Results and discussion

Reactions for the collision system of $^{197}Au+^{197}Au$ at 0.4A GeV with different impact parameters have been simulated by IQMD model under the soft EOS with momentum-dependent interaction (SM+MDI). In this work, the physics results are extracted at 200 fm/c when the reaction system has been at the freeze-out stage. Fig. 1 and Fig. 2 shows the anisotropic flows v_1 as a function of rapidity and the flows per nucleon v_1/A versus rapidity for testing the effect of the number of nucleon scaling, respectively, at different centralities with two sets of in-medium nucleon-nucleon cross section. In Fig. 1, we show the trend of the directed flow v_1. We found that the directed flow (slope in mid-rapidity) is positive, indicating the repulsive nucleon-nucleon interaction are dominant, which is opposite to negative slope v_1 at low energy [18] where the attractive mean field plays a key role. It also shows the absolute values of directed flow are larger for heavier clusters at a given rapidity. On the other hand, with the increase of NNCS reduction factor η from the upper panels to lower panels in Fig. 1, the directed flow values seem to drop, indicating the origin of flow most comes from the nucleon-nucleon collisions. After we perform the NN scaling of v_1, we display Fig. 2 where the curves for different clusters almost stay together around mid-rapidity by the nucleon-number scaled v_1/A, which illustrates that the directed flow of the light clusters satisfies the number-of-nucleon scaling.

The panels in Fig. 3 show transverse momentum dependence of elliptic flow v_2 for light clusters at different centralities with two sets of in-medium nucleon-nucleon cross section. From the figure, it shows that elliptic flows are negative and decrease with the transverse momentum p_t. The negative value of v_2 reflects that the light clusters are preferentially emitted out of the reaction plane, i.e. so-called squeeze-out phenomenon, and particles with higher transverse momentum tend to be stronger negative v_2 values, which is opposite to the collision of lower beam energy [18]. In addition, the heavier the clusters, the larger the value of v_2. This behavior is similar to the directed flow. In intermediate energy, it is well known that both the attractive mean field and the repulsive nucleon-nucleon collisions play important roles. At lower energy, the mean field becomes dominant to contribute to the formation of a rotating compound system, so the positive elliptic v_2 is essentially induced by the collective rotational motion [13,36,37]. In that case, the elliptic flow stems from the attractive mean field. However, at mediate energy as here 0.4A GeV, the two-body collision gradually plays important role and the collective expansion is therefore developed. Although the transverse momentum dependence of v_2 (the absolute values of v_2) is similar to the previous results at RHIC energies, the mechanism of the flow is very different in the two different energy region. At RHIC energies, the elliptic flow is mainly driven by the stronger outward pressure [2], and here the elliptic flow is mainly due to the shadowing effects of overlapping participant zone. As for the NNCS effect, the larger η seems to reduce the absolute v_2 values as v_1 case. After we perform the similar scaling of nucleon number as v_1, we observe a nice number of nucleon scaling exists for the elliptic flow per nucleon as a function of transverse momentum per nucleon as displayed in Fig. 4. In comparison to the number-of-constituent quarks scaling of p_t/n at RHIC energies, this

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behavior looks apparently similar in Fig. 4. The results indicate that the production of light nuclei stems from the nucleonic coalescence mechanism.

In Fig. 5 , we show the R_{cp} of light nuclei (p,d,t) as a function of p_T for different central-peripheral pairs in Au+Au collisions at E = $0.4A$ GeV. It is cleanly seen that the R_{cp} curves for proton, deuteron, and triton are obvious different. The multiple nucleon-nucleon scattering effect [38] tends to transform the longitudinal momentum into the transverse momentum, and the effect becomes stronger with the increase in p_T in HICs, which leads to larger R_{cp} in the high p_T region. On the other hand, in the low p_T region, radial flow plays a major role in central collisions, which pushes protons to higher R_{cp} regions and results in the smaller R_{cp} at low p_T. For protons, the strength of R_{cp} enhancement is suppressed at high p_T with the increase in impact parameter as well as in-medium NNCS factor. We noticed that this factor dependence of R_{cp} is quite similar to the results of R_{cp} obtained in Refs. [39,28] due to the multiple nucleon-nucleon scattering effect or/and the radial flow effect.

The upper panels and lower panels in Fig. 5 shows the comparison of R_{cp} of light nuclei with different η values. The η values at 0.0 and 0.5 were used in the simulation of Au + Au at $0.4A$ GeV collisions. In a previous work, the value $\eta = 0.2$, i.e., 80% of the free space nucleon-nucleon cross section was obtained [40]. In fact, the medium effect is different in various ranges of incident energy and matter density [41]. The R_{cp} of light nuclei has an increasing trend with p_T which is explained by the multiple nucleon-nucleon scattering effect as well as radial flow [39], and its trend becomes more rapid for protons with p_T in the low η value case because of the high collision rate between nucleons. Collisions become certainly less in higher η values and it makes the multiple nucleon-nucleon scattering effect less significant. Based upon the above argument, R_{cp} of protons is a good quantity for studying the effect of the in-medium NNCS, it means that we can investigate R_{cp} to draw a conclusion on the in-medium effect by a quantitative comparison between the model and the data.

After performance of the number of nucleon scaling for R_{cp}, Fig. 6 shows the NN scaling of R_{cp} for light nuclei, i.e., $\widetilde{R}^{*}_{cp}$. From this figure, through the number of nucleon scaling, it was found the values of R_{cp} for deuteron and triton can be scaled to proton's after using a constant factor (eg. for panels (a) and (d), a constant factor 1/0.76) on proton's R_{cp}. These constant factors show no dependence on in-medium NNCS factor and weakly depend on centrality. All the above phenomena can be seen as the coalescence mechanism for formation of light nuclei. In comparison to the scaling behaviors of R_{cp} for light nuclei produced from Pb + Pb at 17.2 GeV, Au + Au at 200 GeV, and Pb + Pb at 2.76 TeV [24], this behavior looks apparently similar in Fig. 6. The number-of-nucleon scaling of R_{cp} is increasing as a function of p_T, which could stem from the larger radial flow or multiple nucleon scattering for light nuclei as demonstrated in our earlier work [39]. Therefore it implies that the number of nucleon scaling of R_{cp} for light nuclei supports the viewpoint of the coalescence mechanism for formation of light nuclei at the kinetic freeze-out stage, and this scaling phenomenon is the same as that for elliptic flow [17,18,23]. For the NNCS effect on $\widetilde{R}^{*}_{cp}$, it shows insensitivity due to the cancel effect of the R_{cp} ratio.

4 Summary

In summary, we have investigated the number of nucleons scaling of anisotropic flows, namely v_1 and v_2 for light charged particles produced by $^{197}Au+^{197}Au$ at $0.4A$ GeV where the light particle emission has squeeze-out behavior in the framework of isospin-dependent quantum molecular dynamics model. The different centralities and in-medium NNCS factors are taken into account. The results show that the curves of both v_1/A and v_2/A for different light charged particles stay together, which means that there exists directed flow and elliptic flow scaling on the nucleon number for light charged particles. Then, the number of nucleons scaling of the nuclear modification factor R_{cp} for light charged particles also have been investigated. The results demonstrate that the scaled R_{cp} presents a nice overlap all together after considering a constant difference factor between light charged particles and proton's, indicating a NN scaling of R_{cp} is also satisfied. In light of present study, we propose experimental studies along this direction.

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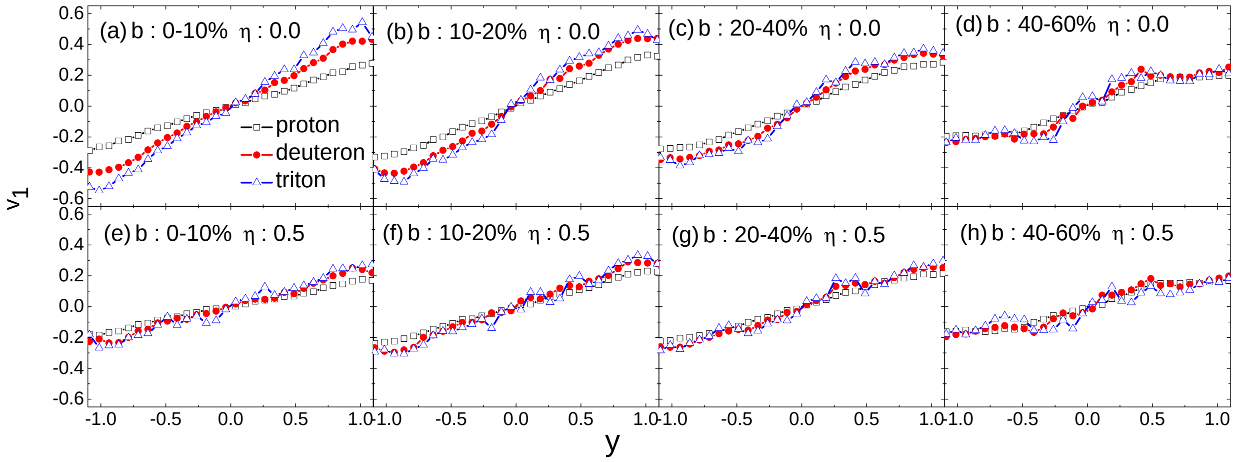

Fig. 1. (Color online) Rapidity dependence of v_1 for light nuclei for 0.4A GeV Au + Au collisions at different centralities. Squares represent for protons, circles for deuterons, up-triangles for tritons. From the left panel to right panel, it corresponds to different centralities of 0 - 10%, 10 - 20%, 20 - 40% and 40 - 60%. The upper row represents the calculations with a factor η of the in-medium nucleon-nucleon cross section 0, and the lower row with $\eta = 0.5$.

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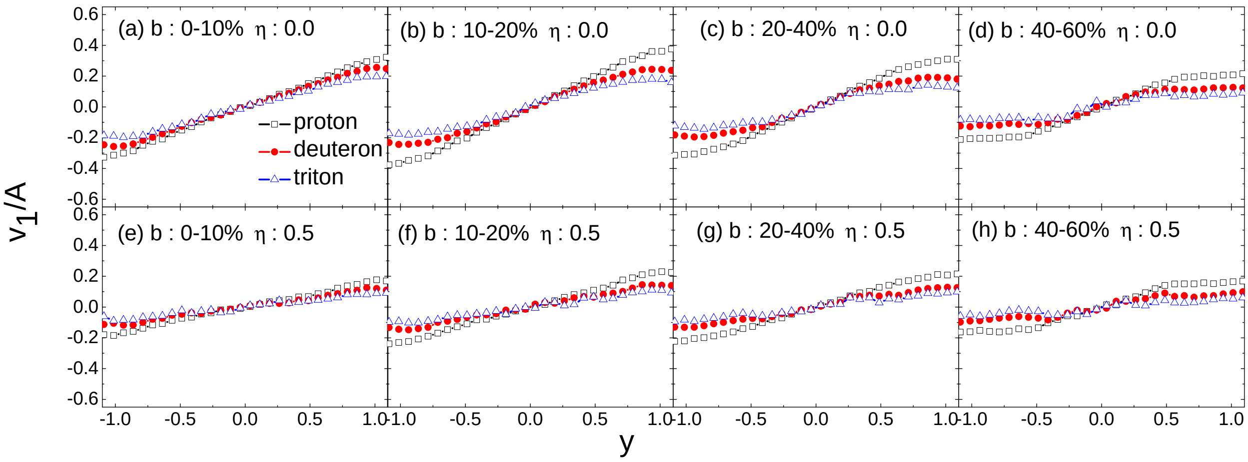

Fig. 2. (Color online) Same as Fig. 1 but for the v_1/A as a function of rapidity.

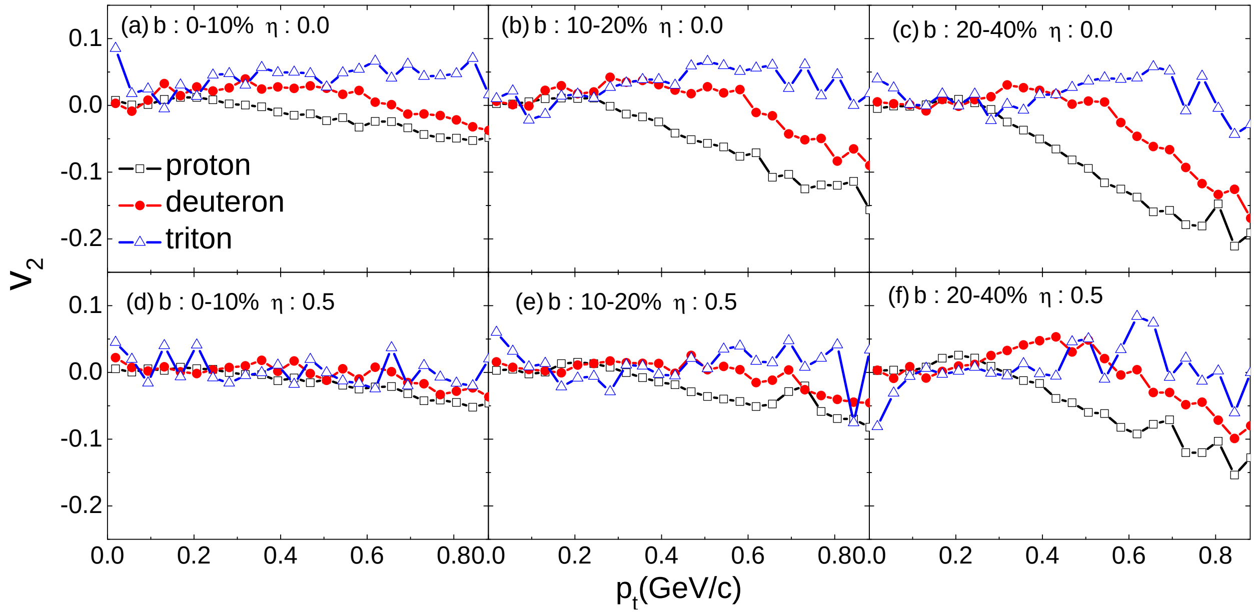

Fig. 3. (Color online) The transverse momentum (p_t) dependence of v_2 for light nuclei in 0.4 A GeV Au + Au collision at different centralities (from left to right: 0 - 10%, 10 - 20%, 20 - 40%). Squares represent for protons, circles for deuterons, triangles for tritons. The upper row represents the calculations with a factor η of the in-medium nucleon-nucleon cross section 0, and the lower row with $\eta = 0.5$.

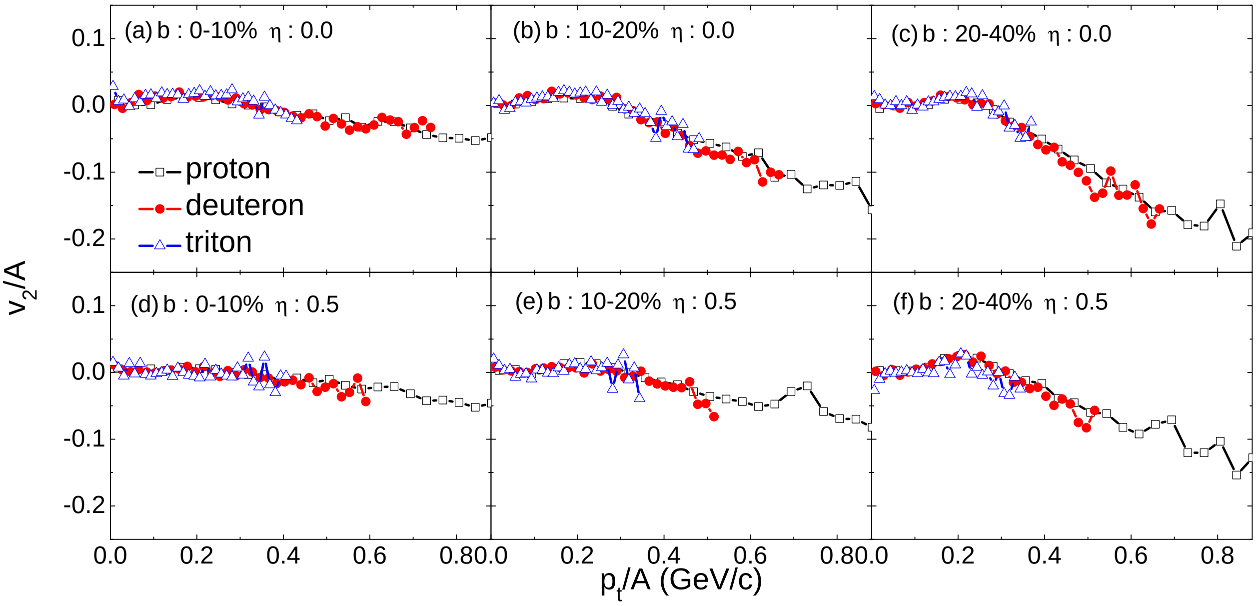

Fig. 4. (Color online) Same as Fig. 3 but for v_2/A versus p_t/A.

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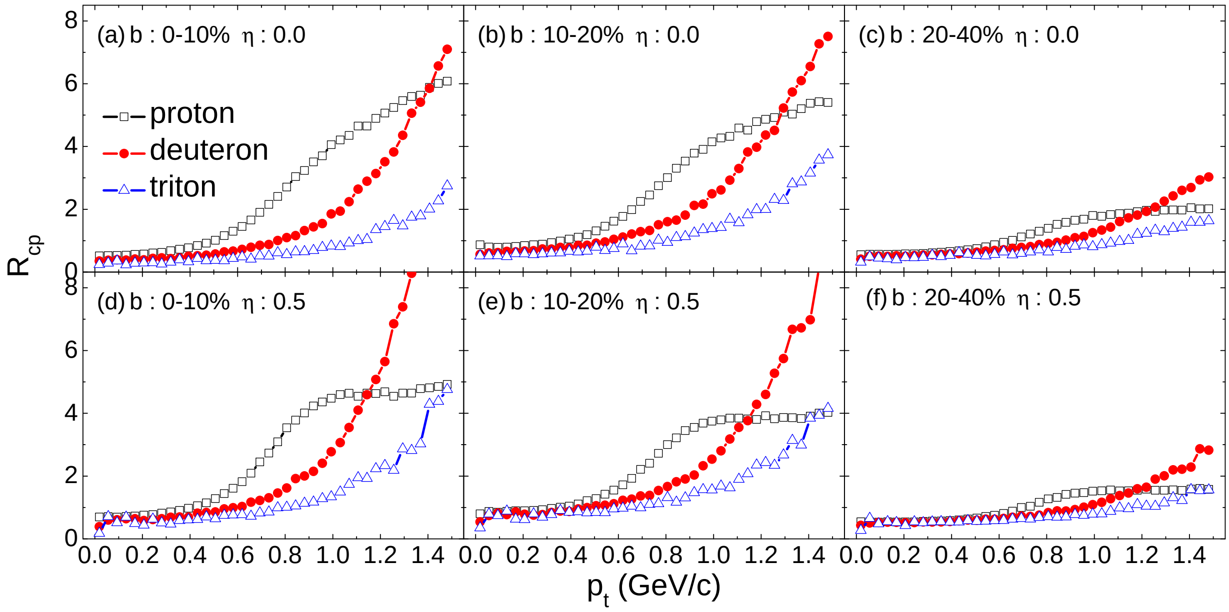

Fig. 5. (Color online) R_{cp} for proton, deuteron and triton in Au + Au collisions at E = 0.4*A* GeV. From left to right, it corresponds to the ratio of different centralities of 0 - 10%, 10 - 20%, 20 - 40% to the centrality 40 - 60%. Two cases of the in-medium NNCS are considered: $\eta = 0.0$ (upper row) and 0.5 (lower row).

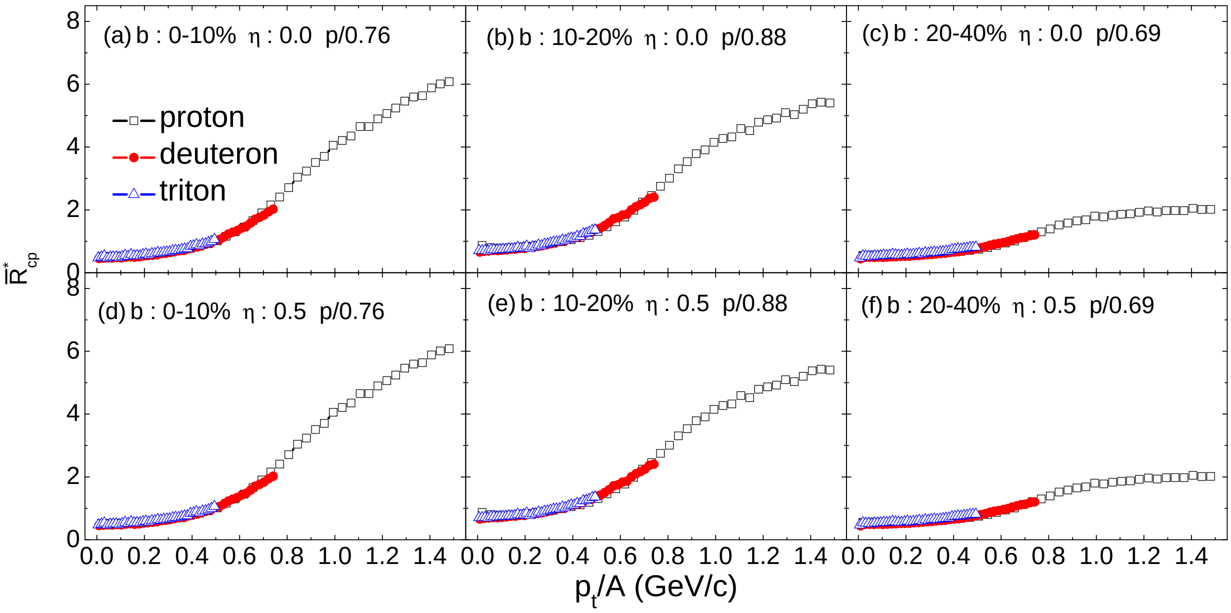

Fig. 6. (Color online) Same as Fig. 5 but for the scaled R_{cp} , i.e. $\widetilde{R^*_{cp}}$.

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